Micro Electrical Discharge Machining of Reaction-Bonded Silicon Carbide

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論文内容要約

Functional micro-structures are gaining more and more importance in the industrial technologies during the last few years. For example, deep micro holes find a wide range of applications in inkjet printer nozzles, spinnerets holes, turbine blades cooling channels, diesel fuel injection nozzles, drug delivery orifices, etc. Another important example is microlens arrays. The ability of microlens arrays to focus incident light into a series of beam spots makes them useful as important optical elements that are widely used in the area of optoelectronic and optical communications. Due to the wide applications of these functional micro-structures in optical, biomedical engineering and microelectromechanical systems (MEMS), micro fabrication techniques have gained growing interest from researchers and engineers.

Recently, the use of reaction-bonded silicon carbide (RB-SiC) as a material in manufacturing optical molding dies for aspherical lenses and microlens arrays has become a new research focus, due to its superior material properties, such as high hardness and strength at elevated temperature, high thermal conductivity, chemical stability, wear resistance and low density. However, due to its high hardness (Vickers hardness 25-35 GPa), it is typically difficult to be machined. Although abrasive machining processes, such as lapping, polishing and grinding can produce a fine surface finish, but the machining efficiency is low and the production cost is high. Diamond cutting is able to produce a high material removal rate, but the severe tool wear in diamond cutting of RB-SiC is the main obstacle that limits its wide application in the industry. Compared to the aforementioned methods, micro electrical discharge machining (micro-EDM) has emerged as a possibly effective machining tool to fabricate complex micro-structures on hard and difficult-to-cut materials like RB-SiC. However, the use of conventional micro-EDM alone to obtain micro-structures with good surface finish and high form accuracy in RB-SiC, is still a challenging issue. The high resistivity of the RB-SiC workpiece is the main limiting factor for the discharge current of micro-EDM, which directly affects the machining efficiency of RB-SiC.

The main objective of this study is to develop hybrid machining processes based on micro-EDM for improving the machinability and surface finish of RB-SiC. Carbon nanofibers assisted micro-EDM was proposed to replace the conventional micro-EDM. The effects of carbon nanofibers addition in the dielectric fluid were confirmed experimentally. The machining mechanism and the material migration phenomenon with the addition of carbon nanofibers were investigated and clarified. Next, a novel machining process, namely hybrid micro-EDM process by combining ultrasonic cavitation and carbon nanofibers was proposed, in order to improve the machining efficiency of RB-SiC ceramic material and to prevent from tool material deposition on workpiece. The effectiveness of the hybrid process was verified through the fabrication of micro-structures on RB-SiC.

This thesis consists of five chapters. Chapter 1 gives an overview of the background of this research.　Firstly, an introduction of the RB-SiC ceramic material, including the fabrication process, material properties, applications and previous machining processes of RB-SiC material were given. EDM was chosen as a method to fabricate micro-structures on the RB-SiC, which can overcome the shortcomings of the abrasive machining process. Then, an overview of the principle of micro-EDM/EDM process was discussed. The problem of machining RB-SiC by using conventional EDM was also pointed out. Some recent developments for enhancing the machinability of hard and brittle ceramic materials by micro-EDM/EDM were reviewed. Finally the objectives and organization of this thesis were stated.

Micro-EDM is primarily an electro-thermal machining process for conductive material. However, the RB-SiC that was used in this study possesses very low conductivity, which made the machining process unstable. This problem becomes more pronounced during the fabrication of micro deep holes and other micro-structures such as micro dimples and micro grooves. Therefore, in Chapter 2, carbon nanofiber assisted micro-EDM was proposed. In this process, carbon nanofibers measuring 150 nm in diameter and 6-8 μm in length were added into the dielectric fluid. Unlike the conventional EDM, carbon nanofibers can arrange themselves in the form of micro chains and interlock to each other, which help to form bridging networks between the electrode and the workpiece. Furthermore, the excellent electrical conductivity of carbon nanofiber (10^{-4} Ωcm) also reduces the insulating strength of the dielectric fluid. To verify the proposed method, firstly, simulation of electric field distribution and direction of the electric force were conducted with a commercial finite element analysis (FEA) software package, COMSOL Multiphysics. It is expected that under the influence of electric force, carbon nanofibers will be concentrated around both electrodes, and will align themselves in the form of chain in the direction of flow of current. The effect of carbon nanofiber on gap width was then studied analytically and verified through preliminary experiments. The experimental results were in good agreement with the analytical study, where carbon nanofibers were more effective in increasing the spark gap and material removal rate of RB-SiC compared to spherical carbon powders. Next, the changes in electro discharging behavior, material removal rate, electrode wear ratio, electrode geometry, spark gap, surface finish, surface topography and surface damage with carbon nanofiber concentration were examined experimentally. It was found that the addition of carbon nanofiber not only improved the electro discharge frequency, material removal rate, discharge gap and surface finish, but also reduced the electrode wear and electrode tip concavity. Micropores and microcracks were found on the machined surface, and the mechanism of micropores formation was different from that in micro EDM of conductive metals. Bidirectional material migrations between the electrode and the workpiece surface were also detected, and the migration behavior was strongly suppressed by carbon nanofiber addition. Adhesion of carbon nanofibers to the workpiece surface occurred, which contributed to the improvement of electro discharge machinability.

Material migration between electrode and workpiece is difficult to be avoided during EDM processes. Especially when performing EDM in the micro/nano scale, the effect of material migration may play an important role from the viewpoint of mechanical and physical properties of the machined surface. In order to clarify its fundamental mechanism, in Chapter 3, material migration between tool electrode and workpiece material in micro-EDM of RB-SiC was experimentally investigated. The microstructural changes of workpiece and tungsten tool electrode were examined using scanning electron microscopy (SEM), cross-sectional transmission electron microscopy (TEM) and energy dispersive X-ray spectroscopy (EDX) under various voltage, capacitance and carbon nanofiber concentration in the dielectric fluid. The RB-SiC that was used in this research, consists of crystalline 6H-SiC grains and crystalline bonding silicon. During the EDM process, the Si matrix, in conjunction with sintering agents, possesses a higher electrical conductivity than the 6H-SiC grains, so it was preferentially removed by melting and vaporization, leaving craters on the surface. The melted tungsten electrode particles were deposited intensively inside the discharge-induced craters on the RB-SiC surface as amorphous structure forming micro particles, and on flat surface region as a thin interdiffusion layer of poly-crystalline structure. The formation mechanism of the subsurface layer in this work was distinctly different from those in mechanical machining processes such as diamond turning, which mainly phase-transformed from the bulk material by mechanical stresses. Deposition of carbon element on tool electrode was also detected, indicating possible material migration to the tool electrode from workpiece material, carbon nanofibers and dielectric oil. Material deposition rate was strongly affected by workpiece surface roughness, voltage and capacitance of the electrical discharge circuit. For reducing the migration and deposition of tool material, the capacitance should be kept as low as possible and the voltage at moderately high level. Adding carbon nanofibers into the dielectric fluid at a concentration of 0.06 g/L was helpful. These findings are useful for improving the surface integrity and purity of RB-SiC in micro-EDM.

In micro-EDM, due to the narrow sparking gap, the removal of debris is remaining a challenging issue, especially in deep holes machining and fine finishing with lower discharge energy. The deposition of tool material on the workpiece surface not only caused surface contamination, but also deteriorated the surface finish of the workpiece. Conventionally, orbital electrode actuation, flushing, planetary movement of electrode, ultrasonic vibration, etc were used to overcome these problems. In Chapter 4, in order to suppress the tool material deposition and improve the machining efficiency of RB-SiC ceramic material, a new machining method, namely hybrid EDM process by combining ultrasonic cavitation and carbon nanofibers was proposed. In this method, suitable amount of carbon nanofibers were added and mixed uniformly in the dielectric fluid. An oscillator horn was placed into the compound dielectric fluid and ultrasonic vibration was used to generate cavitation to assist micro electrical discharge machining. For comparison, another two types of micro-EDM tests were then carried out, namely, carbon nanofibers addition in EDM oil only, and ultrasonic cavitation in pure EDM oil. Changes of hole depth, hole geometry, surface topography, machining stability and tool material deposition rate under various machining conditions were investigated experimentally. The results show that the ultrasonic vibration-induced cloud cavitation was very helpful for increasing sparking gap and removing debris, especially when carbon nanofibers were added into the dielectric fluid. The combination of ultrasonic cavitation and carbon nanofibers can improve the maximum hole depth, form accuracy, and surface finish of micro holes to a significant degree. The tool material deposition rate was strongly affected by the ultrasonic vibration amplitude and the distance between the oscillator and workpiece during fine finishing. The main mechanism for removing the debris from the sparking gap was through the oscillation of the cloud cavitation, rather than the collapse of micro bubbles. The cloud cavitation tends to oscillate at the working area due to the pressure fluctuation in dielectric fluid which was induced by low intensity ultrasonic waves. In a cloud cavitation, the nonlinear bubble dynamics produced nonlinear interactive effects which caused cascading of fluctuation energy. This fluctuating energy was helpful to flush out the debris from the working gap. As test pieces, aspect ratio of 21.7 micro deep hole was successfully fabricated on RB-SiC at a high machining speed. Under fine finishing conditions, micro dimples with good cross-sectional profile and minimum tungsten deposition were successfully obtained. The proposed hybrid EDM process has been demonstrated to be helpful for fabricating micro-structures on hard brittle ceramic materials.

In Chapter 5, the general conclusions of this research were summarized.

As a summary, in this dissertation, carbon nanofibers assisted micro-EDM has been developed to enhance the machinability of low conductivity RB-SiC ceramic materials. Material migration phenomena during the micro-EDM process were clarified. The optimal conditions to control the material migration in micro-EDM of ceramic materials and to improve the finished surface topography and surface integrity were confirmed. By using the proposed hybrid EDM process with combination of ultrasonic cavitation and addition of carbon nanofibers in dielectric fluid, tool material deposition was significantly suppressed and machining efficiency was improved 5-7 times compared to the one obtained with merely ultrasonic cavitation or carbon nanofibers addition. With this method, high aspect ratio micro holes and good cross-sectional profile micro dimples with minimum tungsten deposition were successfully fabricated on hard and brittle RB-SiC ceramic material. By applying the new process proposed in this dissertation, the production cycle and cost involved may significantly reduce compared to the conventional process.